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13. ABSTRACT

The Symposium on Biodynamics Models and Their Applications took place in Dayton, Ohio, on 26-28 October 1970 under the sponsorship of the National Academy of Sciences - National Research Council, Committee on Hearing, Bioacoustics, and Biomechanics; the National Aeronautics and Space Administration; and the Aerospace Medical Research Laboratory, Aerospace Medical Division, United States Air Force. Most technical areas discussed included application of biodynamic models for the establishment of environmental exposure limits, models for interpretation of animal, dummy, and operational experiments, mechanical characterization of living tissue and isolated organs, models to describe man's response to impact, blast, and acoustic energy, and performance in biodynamic environments.

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PAPER NO. 27

AN APPROACH TO HEAD IMPACT ANALYSIS

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ABSTRACT

Presently, many mathematical models of response to head impact are based on a thin elastic shell filled with an inviscid fluid. While these models serve as starting points, anatomic and physiologic considerations indicate that many areas for improvement exist. Research has been recently initiated to determine the behavior of the multi-layered viscoelastic and elastic-plastic brain protection system in response to impact loading.

Geometrically simplified layered mathematical models are proposed to evaluate the importance of viscous, plastic, and layering effects within the model. Dynamic material testing has been performed on photoelastic models to demonstrate stress wave propagation through the cavities within the diploe region.

INTRODUCTION

As a consequence of man's travel at increasing speeds, the incidence and severity of head injuries has also increased. The importance of protecting against head injuries can be readily observed by considering that the present Naval pilot replacement cost is over two million dollars per pilot. A more complete understanding of the mechanical mechanisms involved in impacts to the skull will be useful in two ways: 1) explaining the occurance of post-traumatic symptoms and 2) leading towards the development of a better protective system.

Engin[1], Benedict[2], and Advanti and Lee[3] have proposed fluid-filled spherical shell models of the head. These approaches have considered the shell wall, which is analagous to the skull, to be elastic, isotropic, and homogenous. An inviscid compressible fluid represents the brain matter The Engin[1] and Benedict[2] models consider the walls to be thin, while the Advanti and Lee[3] formulation inlcudes a moderately thick shell with transverse shear and rotary inertia. These shell theories represent useful approaches for indicating areas of potentially dangerous mechanical stress. Engin and Liu[4] suggest a further step would be the inclusion of an opening in the sphere which would simulate the foramen magnum.

Anatomical and physiological considerations suggest that the skull contains three layers of materials which exhibit viscoelastic and elastic-plastic constitutive relationships. A complex CSF-meningeal systems plus an energy absorbing scalp also act to protect the viscoelastic brain. (Figure 1). The various material properties in the many brain protection layers, the ordering of layers, and the coupling between layers are areas of potential importance in head impact analysis. Therefore, it is the object of this study to consider the effects of a multi-layered brain protection system in response to impact loading

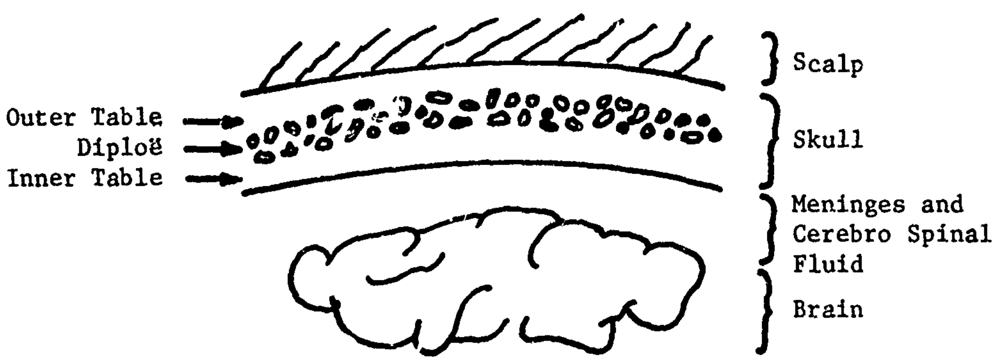

Figure 1. SKETCH OF HEAD CROSS-SECTION

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FORMULATION

As recently as 1968, Ommaya[5] surveyed publications on the mechanical properties of the nervous system. He reported that only three major brain tissue property papers had been presented. Also, very scant findings were given for the other constituents of the nervous system. The material properies of tissues of the head in the present model are based mainly on recent publications and the "Final Report on Determination of the Physical Properties of Tissues of the Human Head" by West Virginia Univeristy.[6] As future material information becomes available, it will be incorporated to provide the most realistic results within the framework of the suggested model.

During impact head injury, Galford and McElhaney[7] claim the scalp acts as a cusion in the transmission of the force to the brain. The suggested constitutive relations can be generated by a Maxwell-Kelvin four-parameter model. However, because the four parameter model is not a physical representation of the scalp, individual tests, such as creep compliance or stress relaxation, do not yield a unique model. Galford and McElhaney[7] do not determine any set of parameters for a Maxwell-Kelvin scalp model. Therefore, the present formulation will consider the generalized case with the following governing equation

$$\sigma + p_1 \dot{\sigma} + p_2 \ddot{\sigma} = q_1 \epsilon + q_2 \dot{\epsilon} + q_3 \ddot{\epsilon}$$

Where

σ is stress

ϵ is strain

$\dot{-}$ is 1st time derivative

$\ddot{-}$ is 2nd time derivative

$p \,\&\, q$ are material constants.

The skull structure consists of three layers: the outer, the diploë, and the inner table. The outer and inner tables are constructed of hard, dense bone. The diploë consists of bone with fluid-filled interconnected cavities. Strain rate dependence has been demonstrated for hard femur bone[8]. In testing on the human skull, West Virginia University[6] suggests a certain degree of rate sensitivity in the fresher samples; however, the values for the rate dependence are not yet fully evaluated. Because the tables are the most rigid elements in the layered model being considered, the tables will be assumed to act as purely elastic, isotropic, and homogenious materials with a radial compressive elastic modulus of 5×10^6 psi and a Poisson's ratio of 0.3.

The random variations in diploë thickness do not have a definite functional relationship[6]. The model considered will be assumed to contain an average hole density. Melvin, Fuller, and Bardawala[9] present graphic relations of compression modulus vs. diploë density and of compression strength vs. diploë density. Using average density values the elastic compressive modulus is 2×10^5 psi and the compressive strength is 6×10^3 psi. The Poisson's ratio is assumed to be 0.28[6]. There is some

question as to the effects of strain rate on the stress-strain relationships for the diploë. Melvin, et al.[9] indicate very little scatter of the various rate dependent data points in compressive tests on diploë. However, anatomical observations indicate that the fluid-filled diploë cavities would result in strain rate dependence in the in vivo skull. At present, we shall assume the diploe layer of the mathematical model to be a continuous, homogeneous, isotropic, and elastic-plastic representation of the physiological diploë region, which is porous and in homogeneous.

The elastic, elastic-plastic, and elastic representation of the outer table, diploë, and inner table, respectively, serves as a reasonable first approximation of the three layered skull. This present model is very similar to the honeycomb sandwich structure suggested by Melvin, et al.[9].

The dura will be excluded for the present because of the added mathematical difficulties involved with the inclusion of another layer. The CSF will also be excluded because it has a density and viscosity which are similar to that of the brain. After the mathematical difficulties of a layered viscoelastic model are successfully overcome, the addition of other layers may be accomplished with greater ease.

Brain tissue properties have been investigated recently by several researchers. Mathematical and experimental techniques have been demonstrated for determining the complex shear modulus[10,11]. The brain tissue will be assumed to act as a viscoelastic, isotropic, and homogeneous material. Two possible stress-strain relationships for brain tissue response to compressive loads are found in the literature. Galford and McElhaney[7] suggest a four-parameter Maxwell-Kelvin model as shown below in Figure 2.

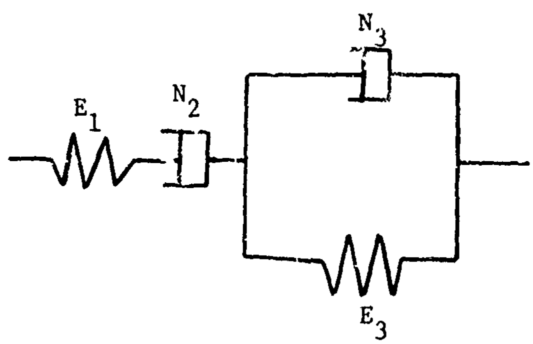

Figure 2. MAXWELL-KELVIN MODEL

The parameters for human brain are given as E_1 (psi) = 3.4, E_2 (psi) = 9.3, N_2 (lb-sec/in^2) = 257.4, and N_3 (lb-sec/in^2) = 8.6. Estes and McElhaney[12] describe the following stress-strain relationship:

$$\sigma = e^{a} \dot{\lambda}^{1-b} \frac{(\lambda-1)^{b}}{\lambda}$$

Where: $\lambda = e^{\epsilon}$, a = 0.50, and b = 0.782.

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Besides the constitutive equation, the layers within the mathematical model must satisfy the basic conservation laws of mass, energy, and momentum. In evaluating the importance of material properties, ordering of layers, and coupling between layers, a geometrically simplified finite dimensioned flat plate model will be used. Because reflected stress waves returning from the far end of the brain layer are of lesser importance in demonstrating the effect of layering in the brain protection system, the brain layer will be assumed to be semi-infinite in depth. Eventually, flat sections and future curvilinear segments might be jointed by suturing analogues to form a final closed container model. Figure 3 shows the ordering of material properties for the mathematical model layers.

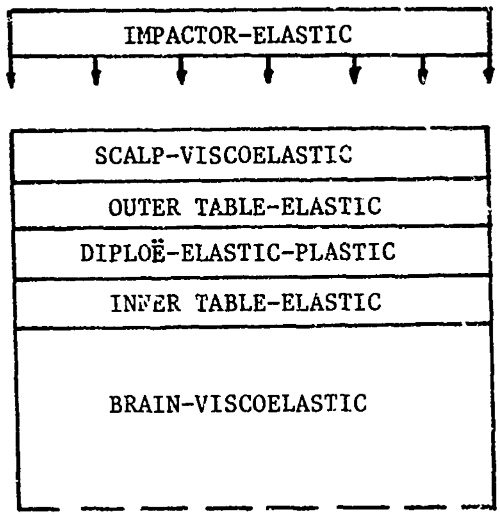

Figure 3. MATERIAL PROPERTIES FOR MODEL LAYERS

The choice of boundary conditions between layers is critical. The three layers of skull material will be rigidly attached to each other. The scalp and brain must be loosely attached to the outer and inner tables. However, it was shown by Janssen and Bowman[14] that the inclusion of a dura attachment to the skullproduced results which differed from the unattached tests. Therefore, some partial attachment might be considered.

In general, the solution technique dictates the precise formulation of the problem. At present, there is no definite decision as to which solution approach will be the most advantageous; therefore, a more concise reduction of the equations which must be satisfied will not be presented at this time.

EXPERIMENTAL METHODS

A representative photoelastic model of the skull was discussed by Melvin et al. and the West Virginia University report. Both studies showed the high stress levels within the diploë region under static compressive loading. A dynamic study of the diploë photoelastic model would be useful in showing how the waves pass through the diploe and indicating any sources of energy loss. To investigate this dynamic situation, the exploding wire facilities of the Drexel University Experiment Wave Propagation Laboratory[15] were used.

A 12.6 mil copper wire 7 1/4 inches long is exploded by discharging 17,000 volts across the ends. Energy is supplied to the wire from a 14 micro-farad 20,000 volt energy discharge capacitor. The exploding wire applies high pressure gas on the edge of a thin plate, generating plane stress waves in the photoelastic plate specimen. The specimen is mounted in a polariocope and the fringe motion recorded by a Beckman-Whitley model 201 high-speed framing camera. The camera uses an air-turbine mirror system to achieve a framing rate of 1 μsec between frames. The wave front is observable as a concentration of several fringes in the isochromatic photographs. Light for photographing the stress waves is obtained from an E G and G FX-1C-6 xenon flash tube.

The photoelastic material used was PSM-1 which has an elastic modulus of 340,000 psi and an optical coefficient of 40 psi/in/fringe. The photoelastic model for the three layers of skull is shown in Figure 4. The circular hole is 7/16" diameter. The oblong hole in the lower portion was made with a series of 7/16" diameter holes. Finally, the irregular hole was drilled by a series of 1/4" diameter holes

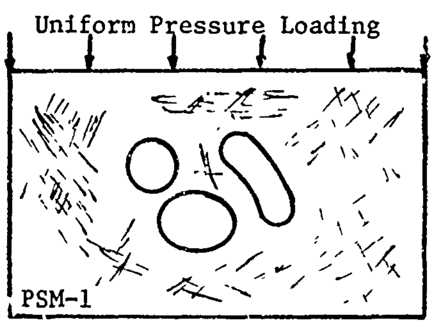

Figure 4. SKETCH OF THE PHOTOELASTIC SKULL MODEL

EXPERIMENTAL RESULTS

Figure 5 shows the results of one dynamic exploding wire test. The stress wave is traveling from left to right in each of the frames. There is a 7 μsec time interval between frame (a) and (b).

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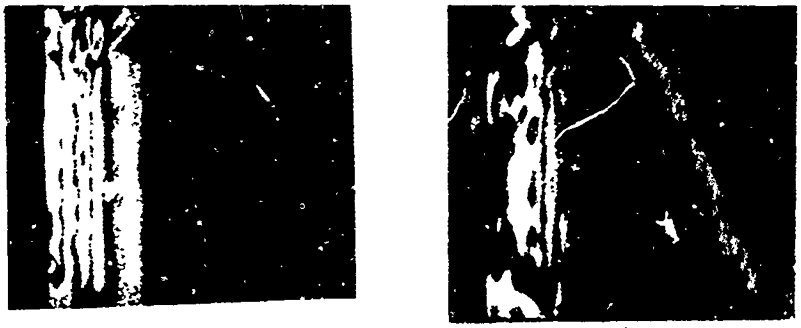

(a) (b)

Figure 5 Stress waves passing through a photoelastic model of the diploe region. (7 μsec between frames)

In Frame (a) the primary wave front is entering the region of the cavity discontinuities. A spherical wave can be seen reflecting from the boundary of the irregularly shaped hole. Frame (b) shows the stress wave as it propagates further into the discontinuity region. A second reflected spherical wave can be observed emanating from the circular hole. As indicated in both frames a portion of the energy is not transmitted through the material; therefore, considerable stress attenuation and wave speed reduction occurs at the wave front.

CONCLUDING REMARKS

The work discussed and suggested here is obviously in its initial phases. The main concept is that of approaching the study of head impact analysis by a more complete consideration of the effects of a layered energy absorbing system.